Achieving Superior Tropical Cyclone Intensity Forecasts by Improving the Assimilation of High-Resolution Satellite Data into Mesoscale Prediction Models

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LONG-TERM GOALS

Forecasts of TC intensity change are often lacking in skill due in part to the paucity of conventional observations over the oceans that are assimilated into the operational models. The inability to accurately map the three-dimensional atmosphere and the underlying upper ocean has also constrained our understanding of how intensity fluctuations are governed by internal and environmental processes. Remotely-sensed observations from multiple satellite sources have become more routinely available as part of the atmospheric/oceanic observing system. As an important input to global numerical data assimilation and forecast systems, these data are providing crucial large-scale environmental information for better predicting such parameters as TC steering flow fields. However, in regard to TC intensity change, it is clear that a dedicated research effort is needed to optimize the satellite data processing strategies, assimilation, and applications within a higher resolution modeling framework. Contemporary strategies developed for assimilating satellite data into global NWP systems appear to be inadequate for retaining information on the scales of processes pertinent to TC analysis and intensity change. Our study attempts to focus on and evaluate the impact of integrated, full resolution, multivariate satellite data on TC intensity forecasts using advanced data assimilation methods and coupled ocean-atmosphere mesoscale forecast models. The development of successful strategies to optimally assimilate satellite-derived data should ultimately lead to improved numerical forecasts of TC intensity.

OBJECTIVES

The ultimate goal of this project is the development and refinement of a capability to supplement the contemporary atmospheric observation network with optimal configurations and assimilation of advanced satellite-derived observations, to improve high-resolution operational analyses and intensity forecasts of TCs.

The primary objectives are to prepare a comprehensive database of full-resolution observations from multiple satellite platforms for selected TC case studies, for provision to the Navy, NOAA and NCAR collaborators in this study and other NOPP-funded studies. Then quantify how best to utilize the multiple satellite datasets in applications to TC structure/intensity prediction, using advanced data assimilation and high-resolution forecast models. Finally, provide a pathway towards advanced satellite data assimilation in the emerging operational TC forecast models (i.e. HWRF, COAMPS-TC).

APPROACH

Our approach is to first investigate and optimize the assimilation of the satellite data in the WRF ensemble-based assimilation system. The COAMPS-TC system is now also being employed in our later efforts. In the evaluation phase, the investigators are analyzing the parallel model analyses and forecasts that assimilate and do not assimilate the satellite data. In this manner, the utility of the various satellite data in improving TC intensity analyses/predictions is being assessed. The main science focus is on investigating and understanding how the assimilation of the satellite data modifies the model analyses and forecasts of TC structure. Moreover, the improvement in model representation of important synoptic features such as adjacent trough interactions, outflow channels, and available environmental moisture is expected to benefit the numerical forecasts of TC intensities. The effects of assimilating data from multiple satellite platforms are being investigated for each individual platform, and for combinations of platforms. Typhoon Sinlaku and Hurricane Ike, both from 2008, have been targeted as primary case studies.

WORK COMPLETED AND RESULTS

This year represents the fourth and final year on which the project is funded. All funds spent this year were via no-cost extensions using funds remaining at CIMSS, NCAR and U. Miami after Year 3. The funds provided to NRL Monterey (PIs: Doyle and Hawkins) were spent by the end of Year 3, and the NRL contribution is documented in the Annual Reports in Years 1-3.

The following tasks have been addressed in the past year (responsible team members in parentheses):

1) Analysis and evaluation of satellite data assimilation experiments using EnKF/WRF (UMiami, NCAR, CIMSS)
2) Advancement of bogus TC insertion that uses satellite information. (CIMSS, UMiami)
3) Presentation of results at conferences and in the peer-reviewed literature. (All)

<u>CIMSS--PI Velden</u>

As described in the previous annual report, a novel bogus ensemble data assimilation approach was developed in order to assess the impact of the enhanced AMV observations at high model resolution (i.e. <4km spacing). It involves sampling an ensemble of bogus vortices from selected parameters given in the tcvitals file, and then assimilating the AMV observations using an ensemble Kalman filter. The resulting ensemble mean analysis was then used to initialize a deterministic forecast using the UW-NMS model. While sacrificing the flow-dependent error covariances implicit in analysis cycling, this method has the advantage of allowing much higher model resolution for a fraction of the computational expense. Initial tests for Ike were encouraging, demonstrating an improvement in the intensity forecast relative to a control case in which no special AMV observations were assimilated. However, additional testing over the full life cycle of Ike (46 separate analyses) revealed that the bogus vortex insertion resulted in an inadequate representation of the environmental flow in the neighborhood of the TC, resulting in an unacceptably large number of AMV observations being rejected by the quality control algorithm. To address this shortcoming, a more sophisticated bogus algorithm is employed and tested in conjunction with a cold-start, short-window (i.e.18-hour) assimilation strategy. Such an approach retains the advantage of high model resolution but also allows for a better representation of the environment in the vicinity of the TC as well as the development of some degree of flow-dependence in the error covariances. This should allow a greater impact of the AMV observations on the resulting high-resolution analysis.

In this reporting period, the scheme has been adapted to work within the Developmental Testbed Center's (DTC) Gridpoint Statistical Interpolation (GSI V3.0) framework, specifically for implementation as a hybrid data assimilation system using the Weather Research and Forecast (WRF) model. Among many other advantages, this permits greater compatibility with other efforts ongoing within our group and the research community at large. Using this scheme, the impacts of enhanced atmospheric motion vectors (AMVs) on analyses of Hurricane Ike (2008) were investigated over 10 separate data assimilation windows, initialized at 00Z and 12Z from 07 SEP 2008 – 11 SEP 2008. The simulations were carried out with version 3.2.1 of the Weather Research and Forecasting Model (WRF) and employed an outer domain with 27-km grid spacing and an inner, vortex-following domain at 9-km spacing. The CTL experiment consisted of a cold-start bogus initialization followed by a 6-hr spin-up period and an 18-hr window during which conventional observations (NCEP PREPBUFR)

were assimilated at 6-hr intervals. The impact experiments (EXP3HR, EXP1HR) augmented the CTL with the assimilation of enhanced AMVs from CIMSS at 3-hrly and 1-hrly intervals, respectively.

Previous results indicated favorable impacts on TC position, minimum central pressure and maximum sustained wind speed as well as potential benefit in obtaining more realistic representation of the surface wind field. These results were confirmed in the present reporting period (Fig. 1). Assimilation of the AMVs in EXP3HR has a significant favorable impact on reducing both mean absolute error (MAE) and bias in 34-knot wind radii in three of the four quadrants (the northwest quadrant is insignificantly, though adversely, impacted) when averaged over all analyses. The results are somewhat more mixed in EXP1HR, with significant improvements in bias in the same quadrants but not in MAE. The asymmetric character of the impact is related to the distribution of AMV observations during this period of Ike's life cycle (light westerly shear resulted in displacement of most AMVs to the east of the center). This asymmetry could be lessened by a refinement of the covariance length-scaling within GSI, further optimization of the static and ensemble-based covariance blend, as well as the use of longer (i.e. 24+ hr) data assimilation windows. The degradation in impact with EXP1HR vis-à-vis EXP3HR could be approached similarly, though there the problem is more complicated and also involves more fundamental issues in high-frequency data assimilation and model (im)balance.

34-kt radii (nm)	CTL	EXP3HR	EXP1HR
NE Quadrant	34.6 (+31.9)	***19.1 (+9.0)***	21.7 ***(+0.5)***
SE Quadrant	33.2 (+23.1)	27.3 ***(+1.5)***	32.2 ***(-2.7)***
SW Quadrant	24.0 (+19.8)	***14.7 (+2.8)***	16.2 ***(-3.2)***
NW Quadrant	23.9 (-10.9)	28.0 (-17.8)	41.1 ***(-35.2)***

Figure 1. Mean absolute error (MAE) of 34-knot wind radii in the four quadrants, averaged over all synoptic times (i.e. 00, 06, 12 and 18 UTC) within all DA windows (sample size=15). Biases are in parenthesis, and statistically significant results are indicated in bold.

CIMSS--PI Li

In order to demonstrate the impact of satellite sounder measurements on TC forecasts, CIMSS scientists have developed a near real time assimilation system (SDAT – Satellite sounder Data Assimilation for Tropical storm forecasts) based on the combination of GSI and WRF and using polar orbit microwave and infrared sounder measurements from the Global Telecommunication System (GTS).

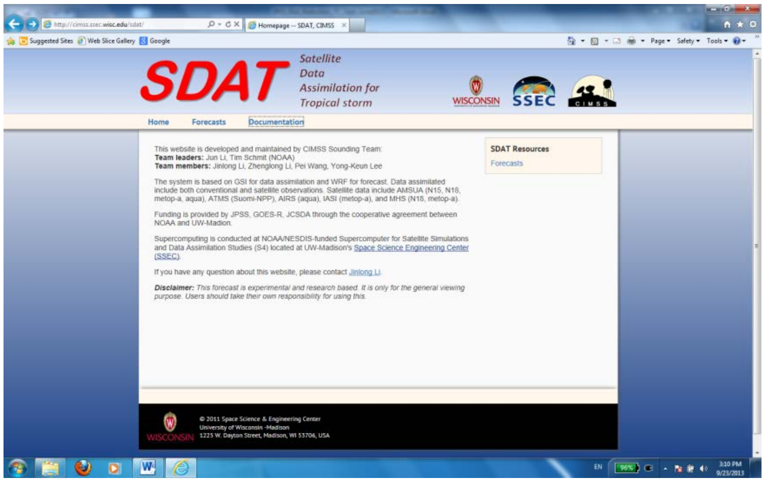
The SDAT system was developed as a research tool and mainly consists of data preparation and data assimilation/forecast parts. The major components include:

- Acquisition of real time GDAS/GFS, conventional and satellite observation data.
- Preparation and conversion of off-line satellite derived products such as soundings (temperature and moisture profiles), total precipitable water (TPW) and AMVs into BUFR format needed by GSI.
- WRF preprocessing system (WPS) to prepare WRF/GSI initial conditions and WRF boundary conditions.
- WRF system to do short-range forecasts (6 hours) to provide the background fields for GSI cycling run and to do a final 72-hour forecast after GSI cycling final analysis.
- GSI system to assimilate both conventional and satellite observations to update WRF model's initial conditions.
- Interfaces between GSI and WRF.
- WRF forecast post processing: diagnostics, plotting, and data archive.
- Webpage for researchers/users to access the forecasts for reference and feedback.

SDAT is running in near real time for tropical cyclone (TC) forecasting in 2013; this accomplishment is supported by NOPP, JPSS and GOES-R programs.

1. Near-real time SDAT

A webpage has been designed for accessing the preliminary results: http://cimss.ssec.wisc.edu/sdat (Figure 2)



(1) Click "Forecasts";
(2) Choose a day and time for forecasts;
(3) Choose and click a variable, for example, "TPW", or "Precipitation";
(4) Click play - you will see the animation for 6, 12, ..., 72 hour forecasts.
When a tropical cyclone is present, the track and intensity (both central sea level pressure and maximum 10 m winds) are also included for viewing.

Figure 2. Webpage for Satellite sounder Data Assimilation for Tropical storm forecasts (SDAT).

Last year's testing with Hurricane Sandy showed promising forecasts when satellite sounder data were assimilated. For recent storms, the forecasts appear sensible when verified against operational HWRF forecasts.

2. Events forecasted by SDAT - examples

The SDAT has been tested offline for Hurricane Sandy (2012) life cycle forecasts. The data assimilated include conventional data and satellite observations from AMSUA/AMSUB, HIRS, MHS, ATMS, AIRS and IASI radiances. The experiments show that SDAT compares favorably against the GFS and HWRF forecasts of intensity for most time periods.

Two recent tropical cyclones over the Atlantic Ocean, Gabrielle and Humberto, were also well reflected by SDAT (Fig. 3). Evaluation of these forecasts is ongoing.

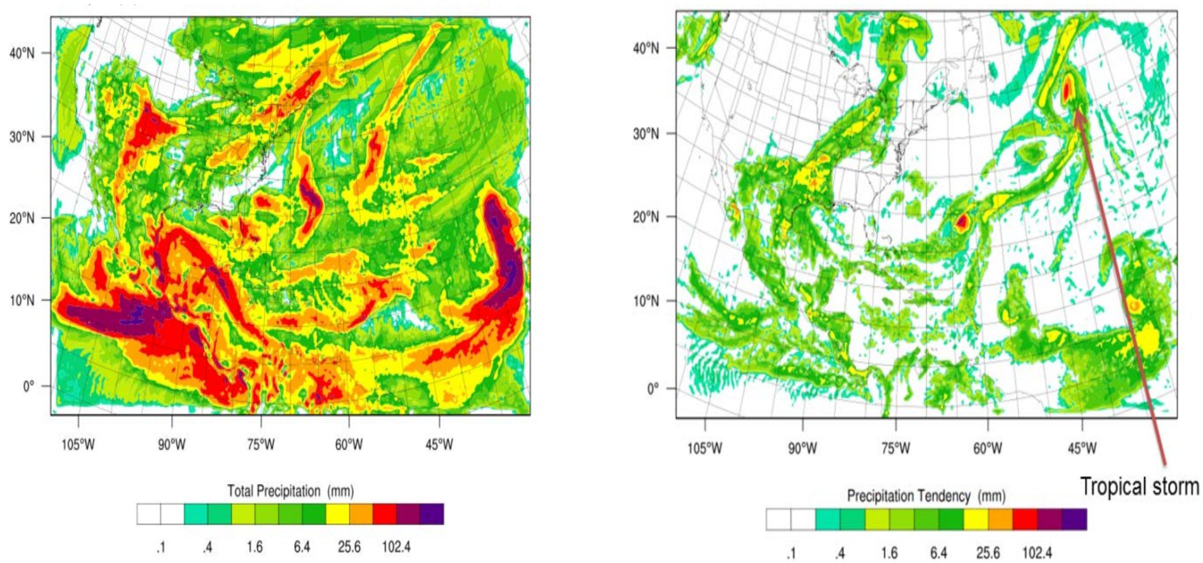


Figure 3. Example of SDAT) 72-hour forecasts of 6-hour total precipitation (left) and precipitation tendency (right), for Tropical Storm Humberto initialized at 0000 UTC 18 September 2013.

3. Radiance assimilation versus retrieval assimilations

The issue of assimilating sounder radiance vs. retrieved vertical profiles has been long debated. The assimilation of transformed retrievals may be particularly advantageous for sensors with a very high number of spectral channels (Migliorini, 2012). Most global NWP centers are using direct assimilation of radiances, based on the successes at both NCEP and the ECMWF. However, due to the challenge of assimilating moisture information, it is still worthwhile to study the assimilation of retrievals for improving direct use of radiances.

We have conducted the following two experiments for examining sounding assimilation versus radiance assimilation, for Hurricane Sandy (2012) forecast impacts:

a) GTS + 4 AMSU-A + AIRS soundings: the AMSU-A from NOAA, Aqua and Metop-A and AIRS soundings retrievals are included, the data obtained through WMO's global telecommunication system (GTS) containing all the conventional data and other related data are also included;

b) GTS + 4 AMSU-A + AIRS radiances: same as (a) but using radiances instead of soundings.

The forecast experiments were conducted in SDAT. Data were assimilated every 6 hours followed by 72 hour forecasts. The assimilation window is +/- 1 hour. Figure 4 shows the forecast RMSE of track and maximum wind speed for Hurricane Sandy. It indicates that retrieval assimilation (blue) is better than radiance assimilation for the track forecasts, perhaps due to the fact that many more clear-sky (TC environment) AIRS channels (~500) are used in the sounding retrievals, while only 128 AIRS channels from the GSI system are used for the radiance assimilation. The forecast maximum wind speed is comparable in the two assimilation trials.

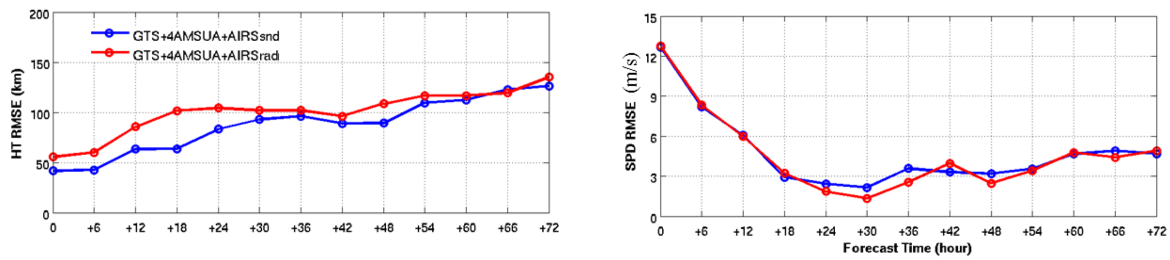


Figure 4. Forecast RMS error of track (left) and maximum wind speed (right) for the life cycle of Hurricane Sandy with 6-hourly assimilation of retrieved soundings (blue) and radiances (red).

UCAR--PI Liu

This past year, NCAR's work was primarily directed to supporting the efforts of the University of Miami on this project. Attention was focused on understanding the impact of the various observation datasets on the analyses and forecast of TC Sinlaku and Ike, as is reported in the U. Miami section below.

In particular, NCAR staff hosted (exclusively with NCAR funding) a 3.5-month visit of Ting-Chi Wu, the UMiami Ph.D. student funded on this project, to NCAR in summer 2013. This enabled Ms Wu to develop a much more in-depth understanding of the WRF/DART assimilation system which was ported onto the NOAA T-Jet supercomputing system. In addition to AMVs which have formed the bulk of Ms Wu's dissertation research (and her first paper), NCAR also worked with her to prepare other satellite observation datasets such as AIRS T/Q and AMSR-E TPW data.

University of Miami--PI Majumdar

Much of the funding remaining on this grant in 2013 was to support Ting-Chi Wu for her Ph.D. study. She is on course to submit her dissertation and graduate in Summer 2014, with funding provided by the University of Miami. The main accomplishments in 2013 have been as follows:

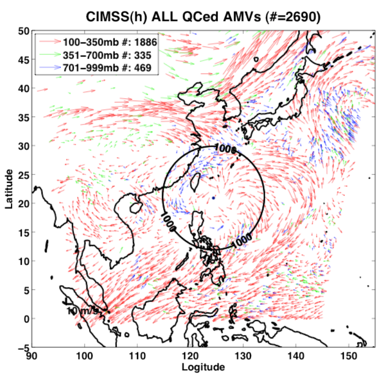
1. **Paper on assimilating AMVs in WRF/EnKF (Mon. Wea. Rev., in press)**

A manuscript (co-authored by U. Miami, NCAR and CIMSS investigators) was submitted and accepted by *Mon. Wea. Rev.* Most of the results have been documented in previous Annual Reports, and are not repeated here. In summary, the assimilation of hourly AMV datasets provided by CIMSS generally improved analyses and forecasts of track, intensity and structure of Typhoon Sinlaku (2008) in the WRF/EnKF analyses compared with the configurations of AMVs that were assimilated in the

NCEP system.   During the period when rapid-scan AMVs were available, analyses and forecasts of the TC and its environment were modified further. The vertical structure of the TC was improved in the analyses due to the assimilation of the rapid-scan data. In contrast to the assimilation experiments without the rapid-scan data, more members in the subsequent ensemble forecast predicted recurvature (which actually occurred), albeit prematurely.

2. Understanding the contribution of subsets of AMVs on analyses and forecasts of TC track and structure

A series of 6 parallel WRF/EnKF experiments (with 84 ensemble members) has been conducted for the same case of Typhoon Sinlaku (2008), in order to understand the relative importance of assimilating AMVs at upper and lower levels, and near and far from the tropical cyclone (Fig. 5)



Expt	Conventional Obs	CIMSS hourly AMVs Assimilated
All	Radiosondes u/v/t/q, aircraft data u/v/t, surface pressure data and JTWC advisory TC position data.	All QC'ed AMVs
Interior		Only AMVs within 10^o radius of TC center
Exterior		Only AMVs outside 10^o radius of TC center
NoLL		Eliminate all low-level (LL) AMVs (700-999 hPa)
NoML		Eliminate all mid-level (ML) AMVs (350-700 hPa)
NoUL		Eliminate all upper-level (UL) AMVs (100-350 hPa)

Figure 5. Left: Spatial distribution of superobbed CIMSS AMVs assimilated in the "All" experiment on 0000 UTC 11 Sep 2008. Right: Summary of the six parallel data-denial experiments (Interior, Exterior and tropospheric layers).

An investigation of the impact on the analysis fields within the tropical cyclone suggested that the interior and low-level AMVs are particularly important for the maintenance of the TC structure. This is evident in the similarity between the 'All' and 'Interior' wind analysis fields, and the difference between the 'All' and the 'NoLL' wind analysis fields (Fig. 6a). On the other hand, the upper-level AMVs were found to be necessary to improve the track forecast (lower left panel of Fig. 6b), whereas lower-level AMVs interior to the TC were necessary to achieve a more accurate intensity forecast (right-hand panels of Fig. 6b).

(a) (b)

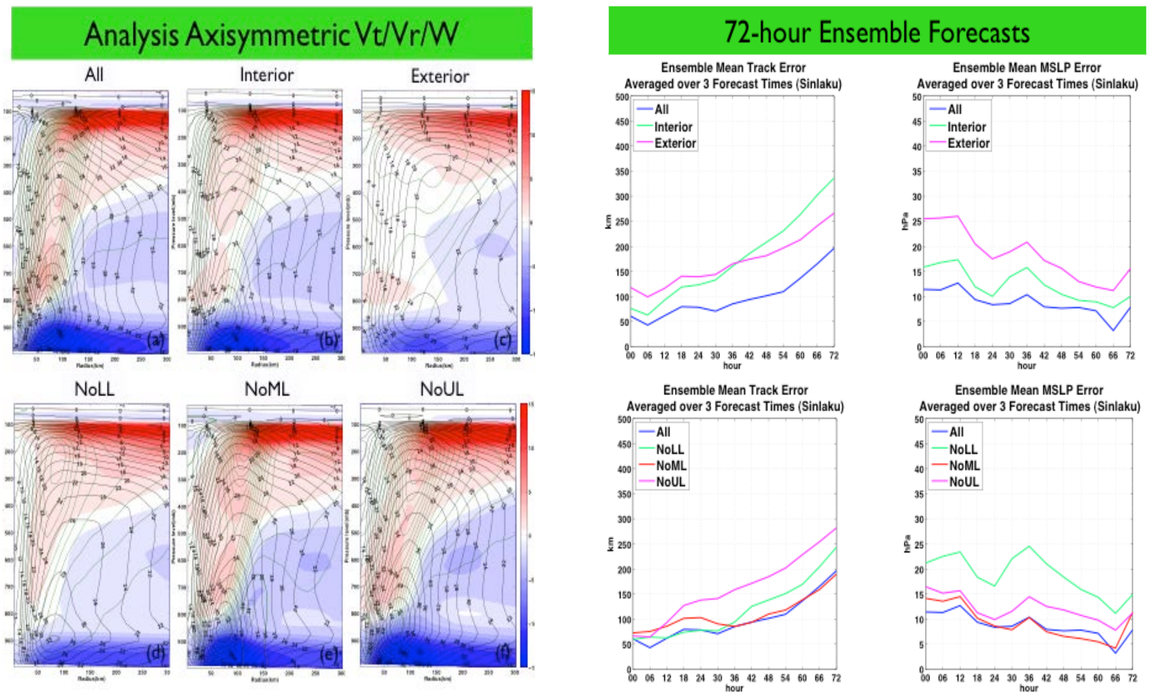


Figure 6. (a) Azimuthally averaged storm-centered radial (red/blue), tangential (black contours) and vertical (green contours) components of the wind in Typhoon Sinlaku (2008), for the 6 parallel experiments. (b) Mean error of the track (left) and the mean sea level pressure (right) of Sinlaku, for the 84 ensemble forecasts (out to 72 h) averaged over three initial times.

3. Parallel study on assimilation of CIMSS AMVs for Hurricane Ike (2008)

Given that the studies to date have mostly focused on Typhoon Sinlaku, it has been necessary to expand the study to other cases to avoid over-interpreting the results from only one TC. As originally proposed, Hurricane Ike (2008) has been added to the sample, with a variety of datasets specially processed by CIMSS and NRL Monterey. In the control simulations without assimilation of specially processed AMV data, the high accuracy in the analyses of the track of Ike (mean errors usually 40 km or less) left little room for improvement, except at the earliest stages. However, the 3-day forecasts were improved using the AMVs during the early stage of Ike's life cycle, particularly when rapid-scan data were assimilated. Only modest improvements to the forecast of Ike's rapid intensification were realized, likely due to the limited resolution of the assimilation and forecast model. Work is ongoing to investigate additional aspects related to the AMV assimilation.

4. Investigation into the assimilation of CIMSS-provided AIRS temperature and specific humidity soundings

The final part of Ting-Chi Wu's Ph.D. study concentrates on the assimilation of thermodynamic observations. Prior to assimilation, the characteristics of the CIMSS-provided AIRS soundings of temperature and specific humidity are being compared against ECMWF analyses (91 vertical levels) and with NASA AIRS Science Team Level 2 products (Fig. 7). A preliminary conclusion is that the

temperature soundings are comparable, whereas the specific humidity soundings have a larger bias in the lower troposphere. Identifying and removing the bias from the CIMSS AIRS soundings is expected to help create more realistic WRF/EnKF analyses and ensemble forecasts. Work is underway to assimilate the soundings with and without the bias corrections in the upgraded WRF/EnKF system.

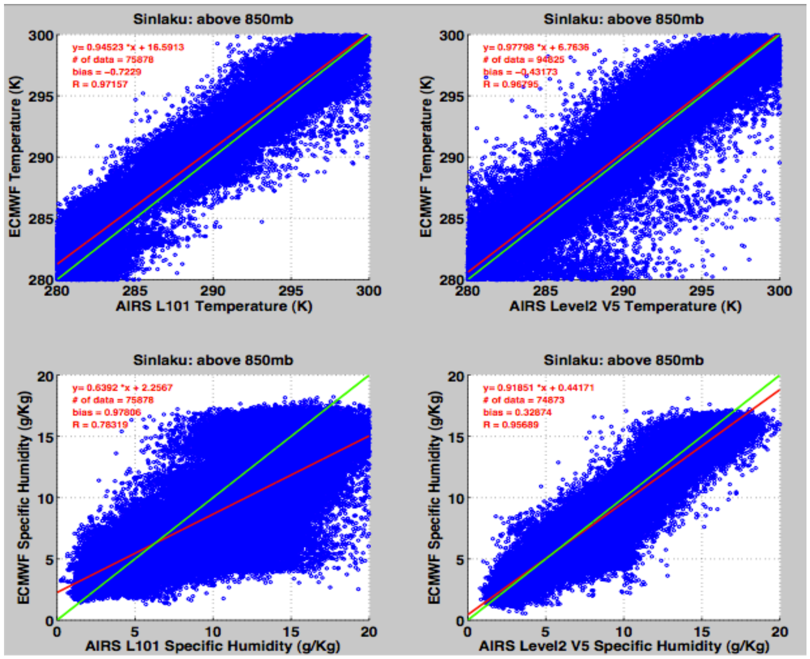


Figure 7. Scatter plot of CIMSS AIRS soundings (x-axis, AIRS L101) versus ECMWF analyses at the sounding locations (y-axis) from above 850 mb collected during Typhoon Sinlaku (2008). Top: Temperature. Bottom: Specific Humidity. Red line: best fit. Green line: unit slope.

IMPACT/APPLICATIONS

The longer-term impact of this study will be derived from the improved assimilation of high-resolution satellite observations in Navy (and other) mesoscale models. These improvements should translate into superior numerical forecasts of TC track, structure and intensity.

RELATED PROJECTS

This project is related to that funded to CIMSS by ONR grant N00014-08-1-0251: "Advanced Satellite-Derived Wind Observations, Assimilation, and Targeting Strategies during TCS-08 for Developing Improved Operational Analysis and Prediction of Western North Pacific Tropical Cyclones" (PIs Velden and Majumdar).

Another project at CIMSS that is related is "High impact weather studies with advanced IR soundings", funded by the NOAA GOES-R program office (PI Li).

Work at UCAR is related to a NASA GNSS proposal: "Improving Tropical Prediction and Analysis using COSMIC Radio Occultation Observations and an Ensemble Data Assimilation System with Regional and Global Models (PI Anderson). Also, a NCAR-CWB (Taiwan Central Weather Bureau) cooperative project "The Enhancement of the CWB Data Assimilation System (PI: Bill

Kuo). Finally, a related NASA proposal submitted and in review "Evaluation of Hyper-spectral IR Data in Storm Forecast with Regional WRF/DART Ensemble Data Assimilation System" (PIs Liu and Li).

This project is also related to that funded to the University of Miami by ONR Grant N00014-08-1-0250: “Using NOGAPS Singular Vectors to diagnose large scale influences on tropical cyclogenesis”. The MATLAB code for dynamic initialization of tropical cyclones developed on that grant has been shared and is being used by CIMSS in their data assimilation studies which use an ensemble of ‘bogus’ tropical cyclone vortices in their first guess field.

Work at NRL Monterey is related to three projects: (i) ONR PMW-120: “Prediction of Tropical Cyclone Track and Intensity Using COAMPS-TC”; (ii) the COAMPS-TC component of the NOAA Hurricane Forecast Improvement Project, and (iii) a NOPP (NOAA/ONR) award on Air-Sea Interaction.

PUBLICATIONS

Wu, T.-C., H. Liu, C. Velden, S. Majumdar, and J. Anderson, 2013: Influence of assimilating satellite-derived atmospheric motion vector observations on analyses and forecasts of tropical cyclone track and intensity. *Mon. Wea. Rev., in press.*

HONORS/AWARDS/PRIZES

Co-PI Majumdar was assigned as Co-Chair of the American Meteorological Society’s annual conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface (IOAS-AOLS), held at the AMS Annual Meeting.

Co-PI Majumdar was appointed Director of the Graduate Program in Meteorology and Physical Oceanography, and Chair of the School Graduate Academic Committee.

Co-PI Velden was awarded the University of Wisconsin Chancellor’s Award for Distinguished Research